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Quantifying Effects of Mid-Frequency Sonar Transmissions on Fish and Whale Behavior

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LONG-TERM GOALS

There are two high-level goals: to understand and quantify effects of mid-frequency (MF) sonar on fish and whale behavior through direct observation, and to investigate the potential usefulness of MF sonar in acoustic measurements of fish, including stock assessments.

OBJECTIVES

The initial objectives are to prove the usefulness of the Kongsberg TOPAS PS18 sub-bottom profiling parametric sonar for observing fish in the water column, and to establish protocols for calibrating the difference-frequency band of this sonar. The TOPAS parametric sonar will then be used as a mid-frequency (MF) sound source, with the aim of collecting data on herring *in situ* in the Norwegian Sea and *ex situ* in pens at the Austevoll Aquaculture Research Station. The data will be analyzed to determine possible behavioral responses of herring to MF sonar transmissions. Ultimately it is the aim to integrate acoustic data on herring with independently collected tagging data from whales to quantify behavioral effects of MF sonar.

APPROACH

This project represents a collaboration with the Institute of Marine Research (IMR), Bergen, Norway, which is conducting a series of sound-exposure experiments at sea to observe the behavioral response of whales and Atlantic herring (*Clupea harengus*) to mid-frequency (MF) sonar transmissions. The sources of the MF sonar signals are the new, Norwegian, Nansen-class frigate sonar, with operating band 1-8 kHz, and the Kongsberg TOPAS PS18 sub-bottom profiling parametric sonar, with primary frequency band 15-21 kHz and difference-frequency band 0.5-6 kHz. The IMR project is entitled "Low frequency acoustics: potentials and dangers for marine ecosystems (LowFreq)," with funding from the Norwegian Research Council. Additional participating institutions in the LowFreq project are the Norwegian Defence Research Establishment, Massachusetts Institute of Technology, Woods Hole Oceanographic Institution, and Kongsberg AS.

The approach is intended to augment the Norwegian LowFreq Project in a number of ways. These are arranged by task.

Task 1. Observation of herring by parametric sonar. The PI, K. Foote, is participating on cruises with Norwegian research vessels to observe Norwegian spring-spawning herring *in situ*, especially during the wintering period off the northwest coast of Norway. The first aim of this work is to establish the

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acoustic detectability of herring with the TOPAS parametric sonar difference-frequency band, which was proposed by the PI to IMR colleagues in 2003. Given measureable echoes, the second aim is to establish the quantifiability of herring by the same difference-frequency band, including measurement of numerical density and sizing based on excitation of swimbladder resonance. The PI will participate in analyses of the data, especially through application of calibration data (Task 2) and developed range compensation functions (Task 3).

Task 2. Development of standard-target calibration protocols for parametric sonar. The PI will lead development of these protocols, already commenced through the design of a standard target for calibration of the difference-frequency band of TOPAS, namely a 280-mm-diameter solid sphere of aluminum alloy (Foote et al. 2007). It is noted that measurement of fish in the upper water column will be made in the TOPAS nearfield, where the difference-frequency wave is being formed, hence the calibration measurements will be made at several ranges. In addition, the high directionality of the difference-frequency wave will require precise target positioning in the transducer beam, which can be accomplished by using an auxiliary sonar operating at an ultrasonic frequency. The PI will participate in the initial calibration trials in the Norwegian Sea, and participate in the analysis of forthcoming data, providing necessary guidelines.

Task 3. Development of range compensation functions for parametric sonar. Range compensation refers to the process whereby the range dependence of echoes, due to geometrical and absorption effects, is removed so that the resulting quantity depends only on the acoustic properties of the targets and their position in the transmit and receive beams of the observing sonar. The PI will develop range compensation functions, called time-varied gain (TVG) functions when applied electronically (Medwin and Clay 1998), for use in measuring the target strength (TS) of resolvable single targets and the volume backscattering strength (S_v) of dense layers of targets, hence of herring in states of relative dispersion and dense aggregation, respectively. For conventional sonars, two range compensation functions are particularly useful. For TS measurements, the echo strength in the logarithmic domain is increased by adding the quantity $40 \log r + 2\alpha r$, where r is the target range, typically expressed in meters, and α is the absorption coefficient, typically expressed in decibels per meter. For S_v measurements, the echo strength is increased by adding the quantity $20 \log r + 2\alpha r$. The situation is more complicated for sonars in which measurements are made in the nearfield of the transmit array. This is the case for the TOPAS parametric sonar when applied to fish in the upper water column, for the difference-frequency signal is literally being formed at ranges where backscattering is being measured. It is noted that significant TOPAS echoes are invariably received in the farfield of the transducer array used for reception.

Task 4. Use of parametric sonar as a sound source in the MF sonar band. The PI will participate in cruises to observe the behavior of herring *in situ* during the wintering period and *ex situ* in pens to determine the possible presence and magnitude of effects due to the exposure of the herring to MF sound generated by the TOPAS parametric sonar. The PI will participate in analyses of the *in situ* data.

Task 5. Integration of parametric sonar data on herring behavior with other sound exposure data on herring and whale behavior. When other sound-exposure data become available, the PI will participate in the integration of the TOPAS parametric sonar data in an assessment of the overall effects of MF sound on fish and whale behavior. The other sound-exposure data are expected to include measurements made with the new, Norwegian frigate sonar, and observations derived from tags attached to whales in areas where the whales are feeding on fish.

WORK COMPLETED

Task 1: Atlantic herring have been observed *in situ* in their wintering area off the northwest coast of Norway during two cruises with R/V "G. O. Sars," 4-10 December 2008 and 11-19 November 2009. The herring were observed by the PI with the difference-frequency band of the TOPAS parametric sonar. They were also observed concurrently with the Simrad EK60 scientific echo sounder operating at 18, 38, 70, 120, 200, and 333 kHz. The EK60 observations were made simultaneously at all frequencies, with a phasing difference relative to the TOPAS sonar to avoid acoustic interference. The pulse repetition frequency was 1 ping/s for each sonar. The TOPAS transducer is mounted on the hull of the vessel. The EK60 transducers, which are split-beam, are mounted nearby on a retractable keel. The initial observations were made on 7 December 2008 at position (N71.4, E16.3). The herring were aggregated in a layer several hundred meters thick in water of approximate 800-m depth. The observations were repeated with the vessel drifting freely and steaming at the ordinary survey speed of 10 knots. Additional observations were made during the period 13-18 November 2009, but in the middle of an ongoing fishery in the vicinity of (N71, E15). The herring were aggregated in numerous small, dense schools in the upper 500 m, with bottom depth in the range 1500-2500 m. The observations were made underway, with vessel speed typically in the range 3-8 knots, reflecting frequent maneuvering due to the high mobility of the small herring schools, which were also being hunted by killer whales. The observations with the TOPAS sonar were made with a variety of signals, including bursts of continuous waves at 2, 3, 4, 5, and 6 kHz difference frequency; Ricker pulses; and linear frequency-modulated (FM) chirp signals, with bandwidths of 2-6 kHz, among others. The observations with the EK60 were made with 1-ms pulsed sinusoids at 18 and 38 kHz. The herring were sampled by pelagic trawl, confirming the dominance of herring and giving detailed information on their size distribution.

Task 2: Calibration trials were conducted during two different cruises with different vessels and TOPAS parametric sonars. The first calibration trial was conducted with R/V "G. O. Sars" in the Sørfolla fjord, near (67 31'N, 15 24'E), on 10 December 2008. The second calibration trial was conducted with R/V "H. U. Sverdrup II" at Haakonsvern near Bergen on 11 December 2008. The same standard target was used, a 280-mm-diameter sphere composed of the aluminum alloy 6082-T6, fabricated by Kongsberg AS according to specification (Foote et al. 2007). During the calibration trial with R/V "G. O. Sars," with near-horizontal orientation of the hull-mounted TOPAS transducer, the standard target was suspended successively at ranges of 90, 225, and 330 m. The high directionality of the TOPAS beam, with full beamwidth of order 3-5 deg across the difference-frequency spectrum 1-6 kHz requires precise positioning. This was accomplished through concurrent operation of the EK60 scientific echo sounder, with split-beam transducers proximate to the TOPAS transducer. Based on simultaneous split-beam observations at 18 and 38 kHz, the position of the calibration sphere during TOPAS operation could be tracked. The corresponding EK60 data for range and angles in the alongship and athwartship planes have been translated into the reference frame of the TOPAS transducer. Allowance was made for the displacement of the several transducers and for differences in their orientations, in roll and pitch, according to a survey of installation equipment on board R/V "G. O. Sars," performed by Blom AS in 2003.

Task 3: Sonars used in quantitative work, such as fisheries research, typically make measurements in the transducer farfield, where the forms of range compensation are quite simple (Medwin and Clay 1998). This is demonstrably not the case with the TOPAS parametric sonar, where difference-frequency measurements on herring are being made in the nearfield of the parametric array expressed as a virtual endfire array (Westervelt 1963, Foote 2007). This complicates application and even

determination of the appropriate range compensation function. To address the problem, the theory for range compensation in a transducer nearfield has been worked out and applied to parametric sonars. Earlier modeling computations of transmit beam patterns, beamwidths, sound pressure levels, and apparent source levels, which were performed with the Convol5 FORTRAN program (Moffett 2003) based on Mellen and Moffett (1978) and Moffett and Mellen (1981), have been refined and extended to determine functions for application to the TOPAS echo data. The particular computations assume that the sonar is parametric in transmission and conventional, i.e., linear, in reception. The transmit array is modeled as a rectangular piston of dimensions 1100x1035 mm in the respective alongship and athwartship directions, while the receive array is modeled as a rectangular piston, with corresponding dimensions 262.4x1035 mm.

Task 4: Data were collected using the TOPAS parametric sonar on board R/V "H. U. Sverdrup II" as a source of MF sound in exposure experiments on penned herring at the Austevoll Aquaculture Research Station on 12 December 2008. Before beginning transmissions, the TOPAS transducer array was mechanically rotated to the near-vertical orientation, with normal beam oriented slightly downwards from the horizontal plane. However, effects of refraction in the surface layer were strong, and problems with instrumentation at the pen were judged too severe to support the envisioned data analysis. However, during analysis of data collected on herring *in situ* in the Norwegian Sea in December 2008 and November 2009 (Task 1) and development of target-tracking in support of calibration (Task 2), it became apparent that effects on herring behavior can be measured differentially by comparing the volume backscattering coefficient as determined by the several beams. The TOPAS beam is much narrower than those of the nearly collinear EK60 beams, which are, for example, 11 deg at 18 kHz and 7 deg at 38 kHz. This work is ongoing.

RESULTS

Task 1: Atlantic herring were observed off the northwest coast of Norway during both cruises with R/V "G. O. Sars" (Godø et al. 2010). During the first cruise, in December 2008, observations were made on a herring layer with the vessel stationary and underway at 10 knots. Representative TOPAS parametric sonar echograms together with corresponding EK60 echograms at 18 and 38 kHz are presented in Fig. 1. The herring length was 28-36 cm, with mean 32.5 cm. During the second cruise, in November 2009, the herring were in small dense schools, with behavior influenced by the ongoing fishery and hunting by killer whales, among other marine mammals. Representative TOPAS echograms collected with a variety of signal types, together with corresponding EK60 echograms at 18 kHz, are shown in Fig. 2. The herring length was 15.5-37.5 cm, with mean 30.5 cm.

Task 2: Positioning of the standard target in the beam of the TOPAS parametric sonar during the calibration exercise with R/V "G. O. Sars" in Sørfolla fjord on 10 December 2008 has been addressed in a preliminary study (Foote et al. 2010). Results are expressed here in Fig. 3 for the 90-m target range through probability density functions of each of four angles. These are the alongship and athwartship angles in the reference frames of their measurement, namely those of the EK60 split-beam transducers at 18 and 38 kHz, and the polar and azimuthal angles in the reference frame of the TOPAS transducer. The statistical agreement is suggestive. Further results at 90 m are shown in Fig. 4 for the probability density function of the distance between target positions respectively determined at 18 and 38 kHz, again in the reference frame of the TOPAS transducer, but with application of constraints relative to target strength, range differences, and alongship and athwartship angles. The probability density function of target strength is also shown, but without these constraints.

Task 3: The nature of range compensation has been investigated for the general nearfield case (Foote 2009). It has been applied to parametric sonar, conceptually represented as a virtual endfire array in transmission and conventional, linear array in reception. Accordingly, for determination of the volume backscattering strength of an aggregation of scatterers, the measured echo intensity should be modified by multiplying this by the inverse of the product of the one-way absorption factor, square of transmit pressure on axis, and two-way equivalent beam angle, all functions of range. This function has been numerically evaluated for the particular TOPAS sonar transducer. Representative transmit beam patterns for the range-dependent nearfield are shown in Fig. 5. The resulting range compensation functions for single and multiple scatterers are shown in Fig. 6. This second function will be applied to the TOPAS echo data collected on herring (Task 1).

IMPACT AND APPLICATIONS

National Security

Navy operations at sea can be affected by the presence of marine mammals. It is expected that the results of the project will contribute to knowledge of possible effects of MF sonar transmissions on the behavior of whales as well as that of other marine animals, especially including fish.

Economic Development

More general use of MF sonars encompassing both water-column and sub-bottom domains may encourage the application, hence increased production, of such sonars. Parametric sonars are especially attractive in this regard because of their physical compactness relative to the exceptionally narrow beamwidths that they produce at low frequencies.

Quality of Life

Society is concerned about the impact of sonar on marine life. This project is attempting to learn about this impact in a quantitative way, ultimately so that possible adverse effects can be avoided or otherwise mitigated.

Science Education and Communication

Forthcoming results from this project are already being published through the scientific literature and lectures to the public. It is expected that these and other publication and communication activities will contribute to science education, as through academic programs in marine science, as well as to more general science literacy among the interested public.

RELATED PROJECTS

As mentioned in the approach section above, this project represents a collaboration with the Institute of Marine Research (IMR), Bergen, Norway, which is conducting the project "Low frequency acoustics: potentials and dangers for marine ecosystems (LowFreq)," with funding from the Norwegian Research Council. Additional participating institutions in the LowFreq project are the Norwegian Defence Research Establishment, Massachusetts Institute of Technology, Woods Hole Oceanographic Institution, and Kongsberg AS. It is expected that the Center for Ocean Sciences Education Excellence - New England (COSEE-NE) will be assisting the ONR project in disseminating forthcoming results.

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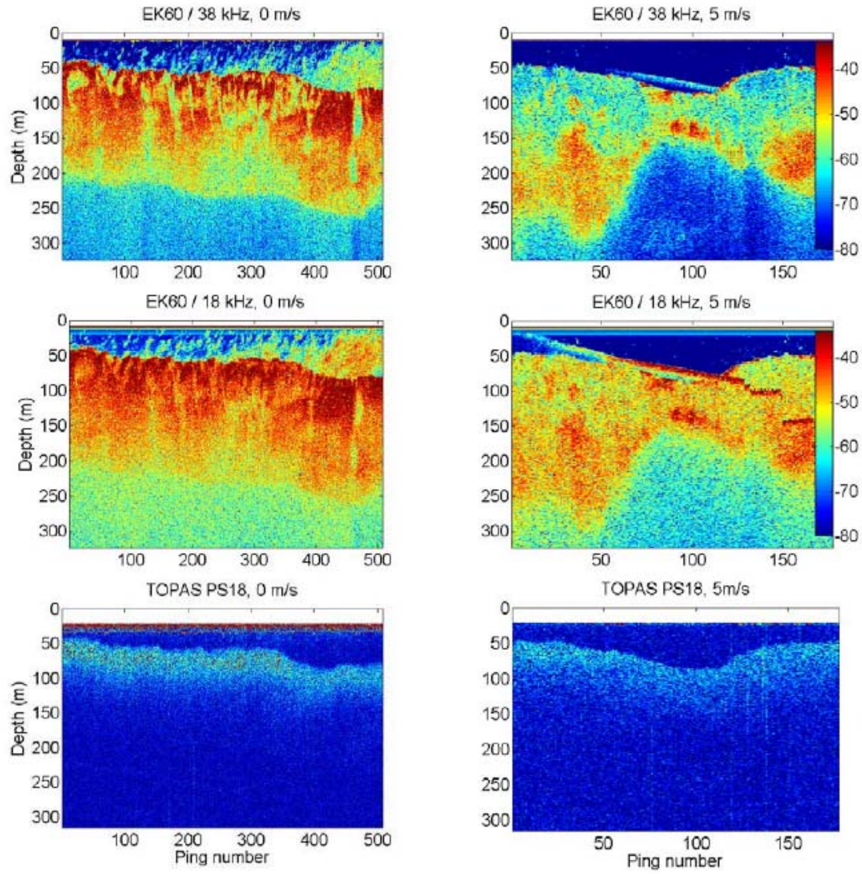

Fig. 1. Two sets of concurrent echograms of Norwegian spring-spawning herring in its wintering area near (N71.4, E16.3) observed from R/V "G. O. Sars" on 7 December 2008. The left set was obtained while the vessel was drifting freely; the right set was obtained with the vessel sailing at the ordinary survey speed of 5 m/s. Echograms obtained with the Simrad EK60 scientific echo sounder display values of the volume backscattering strength in decibels according to the attached color bar. The echograms derived with the Kongsberg TOPAS PS18 Parametric Sub-bottom Profiler involved transmission of a 16-ms FM signal with linear frequency dependence over the band 1–6 kHz, with sampling at 30 kHz after a 20-ms delay, represented by the blank area at the top of the echogram. These data have been match-filtered, but otherwise lack range compensation and calibration. All echograms were derived from measurements made with proximate transducers with vertically downward oriented beams. In the EK60 echograms collected at 5 m/s, there are extraneous signals, probably second bottom echoes, appearing at the surface and descending through the herring records. Reprinted, with permission, from O. R. Godø, K. G. Foote, J. Dybedal, E. Tenningen, and R. Patel, J. Acoust. Soc. Am., 127, EL153-EL159 (2010). Copyright 2010, Acoustical Society of America.

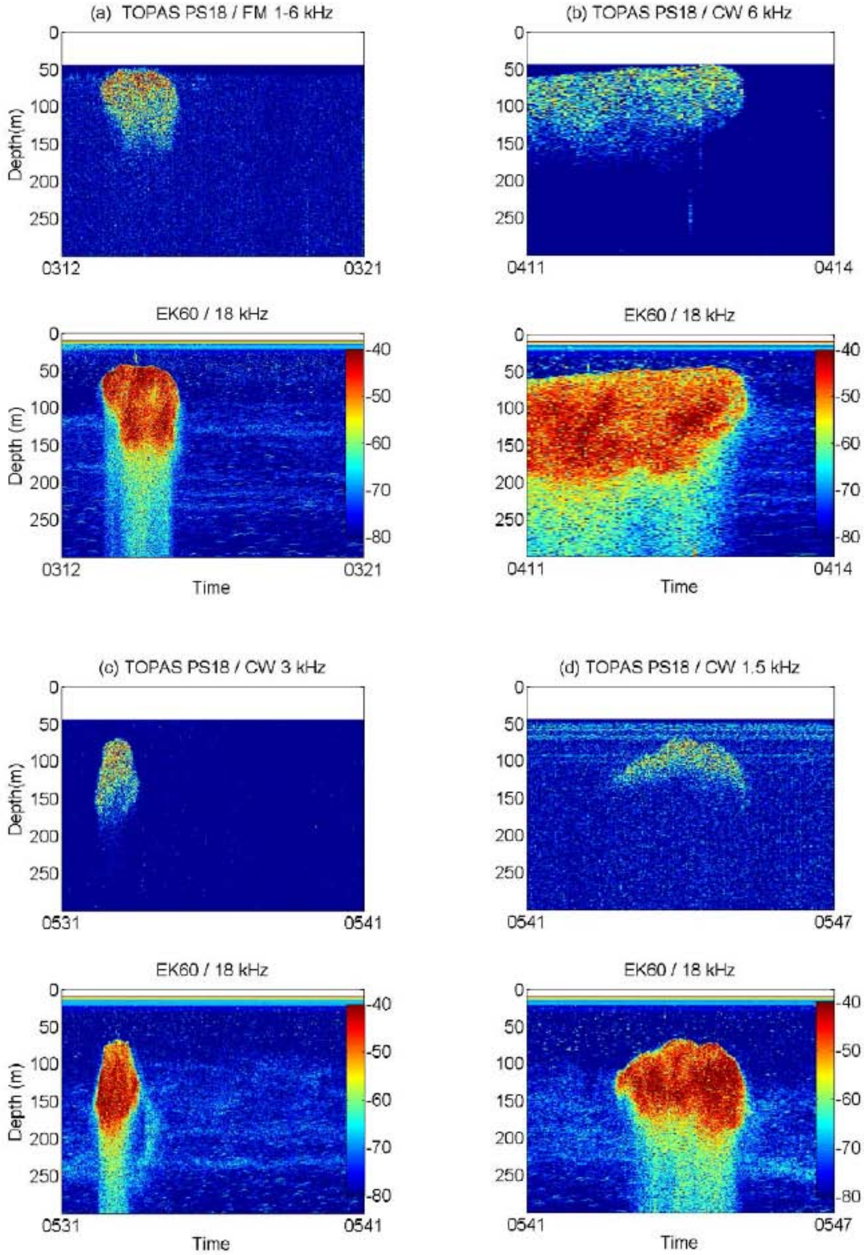

Fig. 2. Echograms collected on the same school of Norwegian spring-spawning herring in its wintering area near (N71.3, E15) on 15 November 2009 during repeated passes with R/V "G. O. Sars" while sailing at 5 m/s. Upper panel: Echograms obtained with the TOPAS PS18 parametric sonar, expressed without range compensation, for each of four transmit signals, with frequency band indicated for the 20-ms duration linear FM signal and with center frequency indicated for the 4-cycle cw burst. Echo data were sampled at 25 kHz following a 50-ms delay, represented by the blank area at the top of the echogram. The TOPAS echoes have been processed by matched filtering for the FM signal and bandpass filtering for the cw signals. Lower panel: Respective echograms obtained with the EK60/18-kHz scientific echo sounder, with 1-ms duration transmission at 18-kHz, expressed as values of volume backscattering strength. Reprinted, with permission, from O. R. Godø, K. G. Foote, J. Dybedal, E. Tenningen, and R. Patel, J. Acoust. Soc. Am., 127, EL153-EL159 (2010). Copyright 2010, Acoustical Society of America.

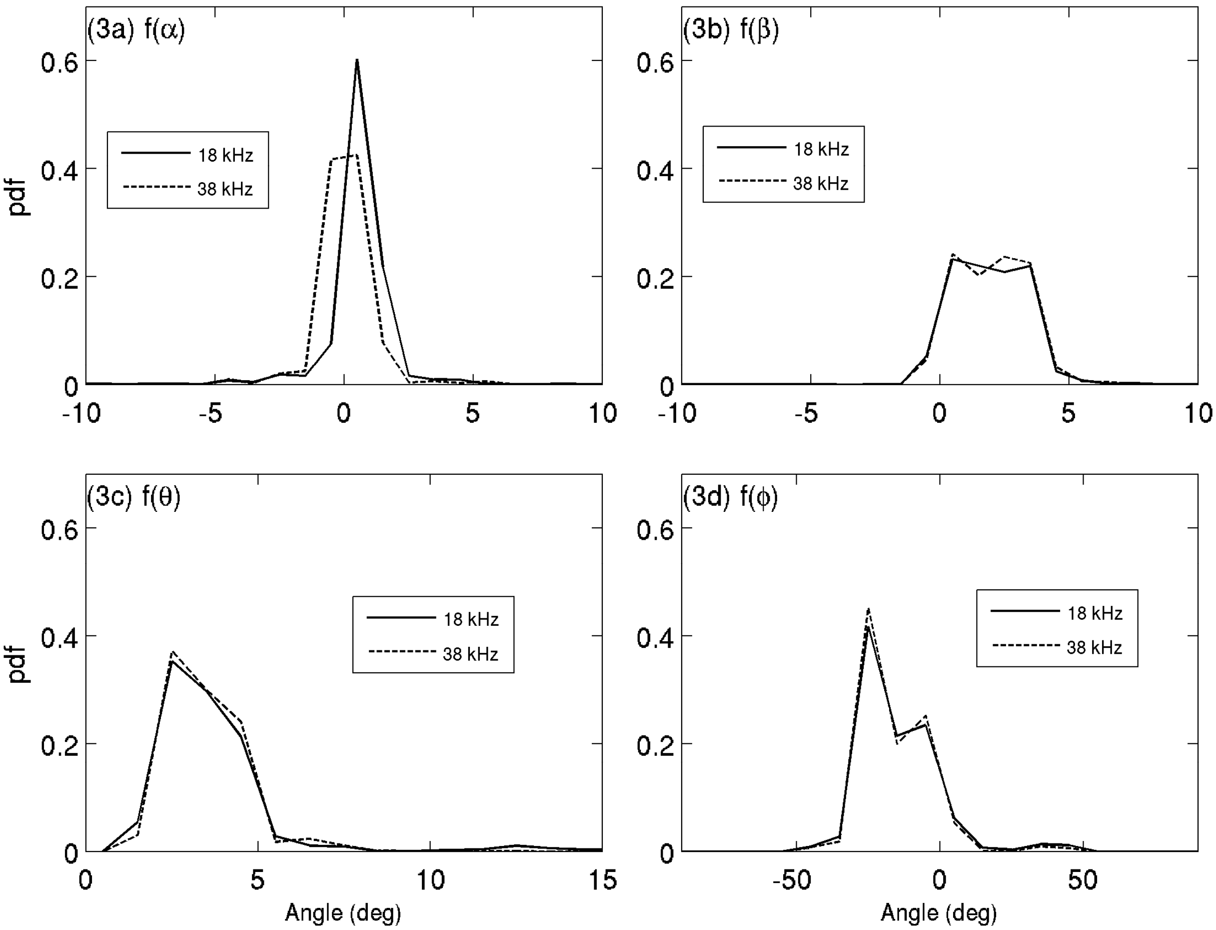

Fig. 3. Probability density functions (pdfs) of angular measurements of target position at approximate range 90 m as derived from the EK60 split-beam scientific echo sounder operating at 18 kHz (solid line) and 38 kHz (dashed line). The alongship angle α and athwartship angle β represent direct measurements. The polar angle θ and azimuthal angle φ are derived in the reference frame of the TOPAS PS18 parametric sonar transducer.

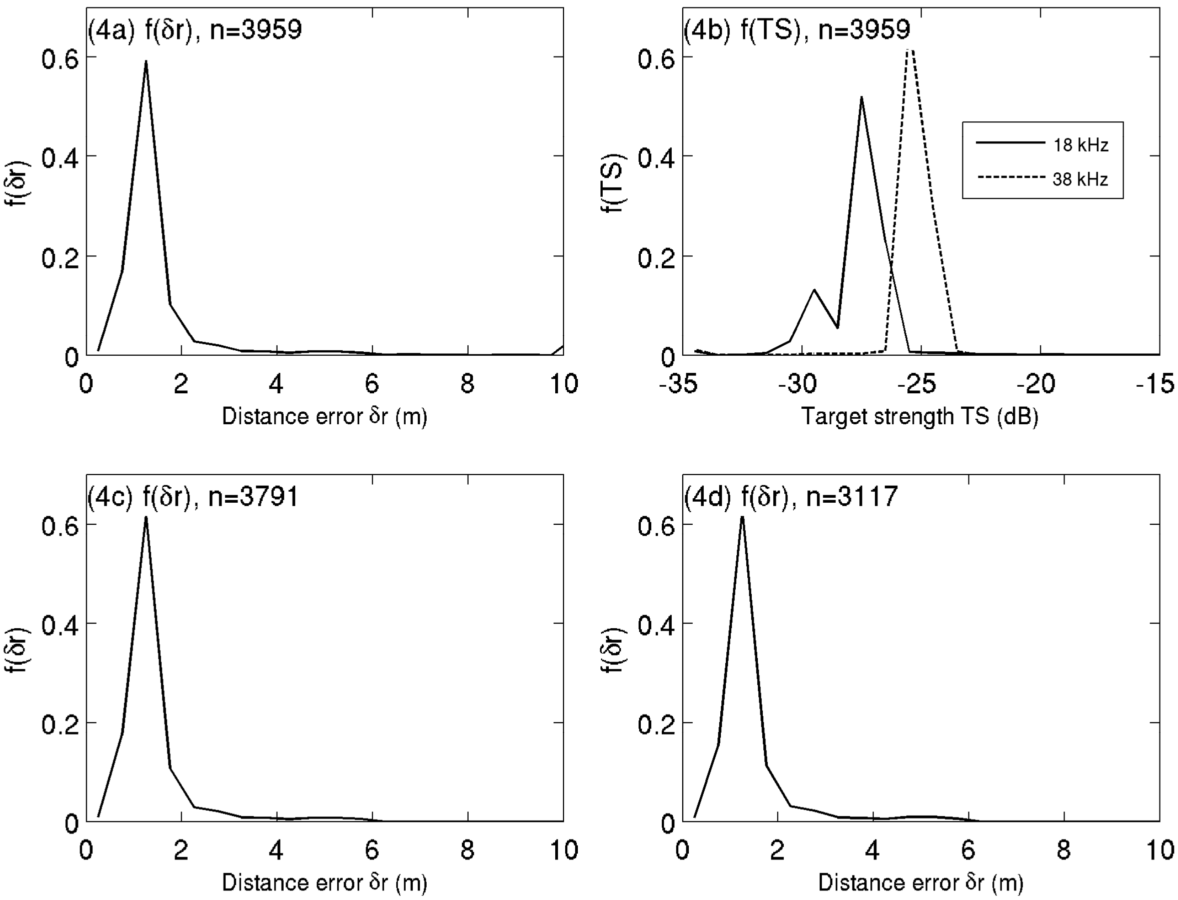

Fig. 4. Probability density functions (pdfs) of distance δr, called distance error, between target positions in the TOPAS beam due to EK60 split-beam measurements at 18 and 38 kHz (parts a, c, d) and probability density functions of target strength (part b). All recorded data were used in parts a and b. Data in part c were derived from those in part a by constraining TS values to lie in the interval [-35,-15] dB and not allowing δr to exceed 6 m. Data in part d were derived from those in part c further constrained by limiting α and β to the interval [-3.5,3.5] deg.

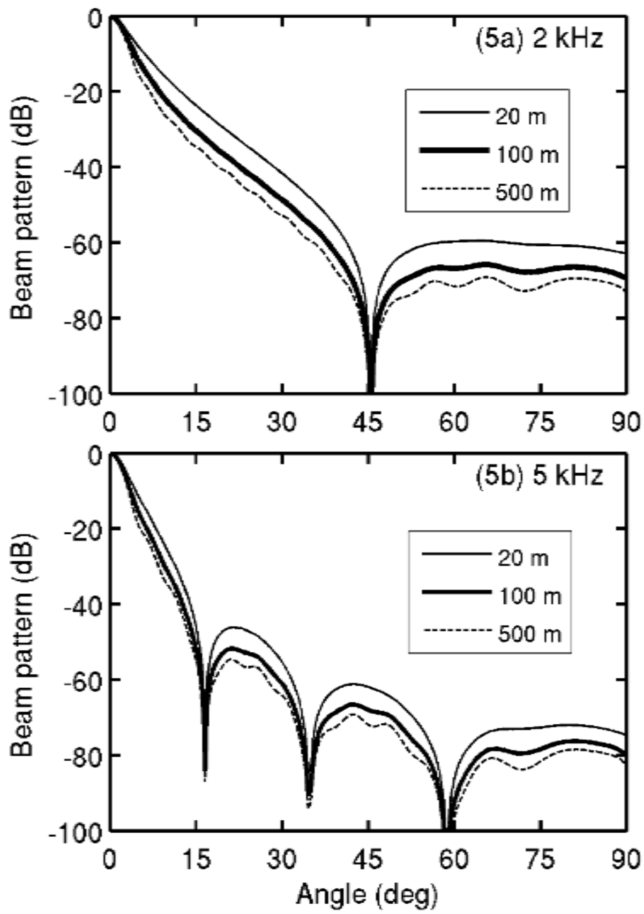

Fig. 5. Transmit beam patterns in the alongship plane of the TOPAS PS18 parametric sonar at the difference frequencies 2 and 5 kHz for each of three ranges for the assumed hydrographic state defined by temperature 5ºC, salinity 35 ppt, pH 8, and depth 200 m

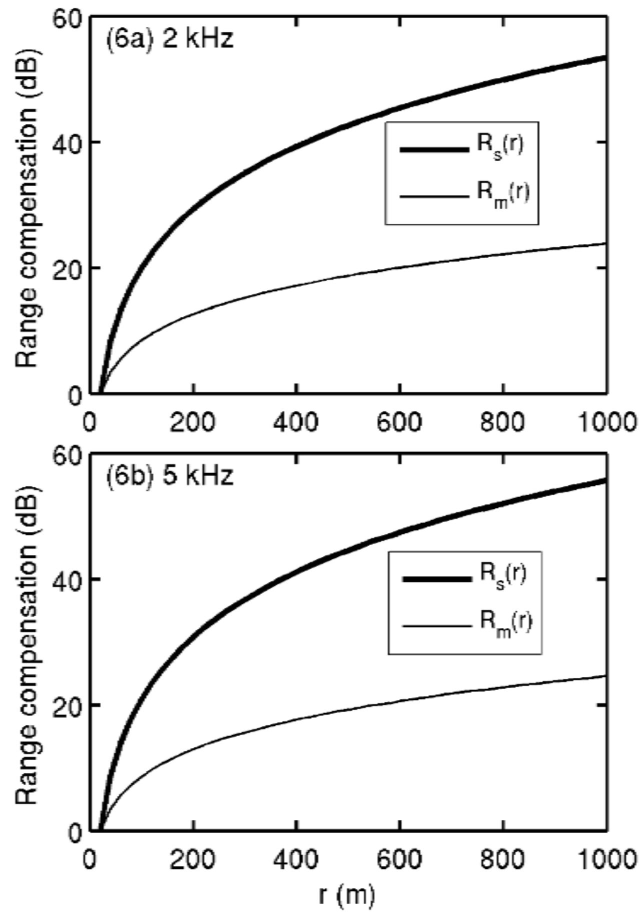

Fig. 6. Range compensation functions for single and multiple targets for the TOPAS PS18 parametric sonar at the difference frequencies 2 and 5 kHz for the assumed hydrographic state defined by temperature 5ºC, salinity 35 ppt, pH 8, and depth 200 m.